# A Modular Model of Infrastructure Interdependencies: Preliminary Analysis of California Electricity Shortages

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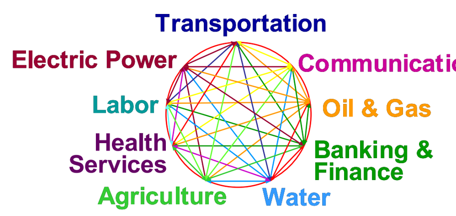
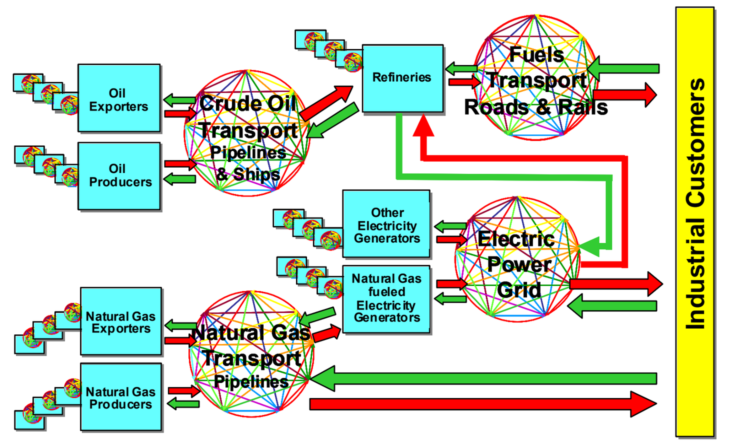
## Introduction

*Infrastructure interconnections create chains of interdependencies that can propagate disturbances across many infrastructures and over long distances.*




*System dynamics modeling can be used to identify chains of interdependencies, arising from pervasive interconnection, which might create unexpected vulnerabilities or robustness.*

*The scope of an infrastructure interdependencies model is necessarily broad; it must include a comprehensive set of interacting components that critical pathways, which might involve distant locations and disparate infrastructures, are represented.*

*System dynamics models can play a crucial screening role in a comprehensive framework for making policy decisions affecting infrastructures.*

*These models allow us to quickly build coarse-grained system simulations that include many interacting infrastructures, and to identify the properties or interactions that might create failure cascades.*

*We can quickly assess the uncertainty in the key results, identifying those areas in which more data or more detailed modeling would provide more conclusive results and less risk in decision making. The results of the screening analysis may, by themselves, provide sufficient resolution to reach decisions. If not, the screening process provides the justification and direction for additional data collection or modeling.*

## A Modular Approach

***Objects in the model fall into one of five basic classes: materials, networks, services, markets, and entities:***

***Materials***

*A material is anything that is exchanged among entities. Examples include natural gas, electricity, water, money, or information. All materials are exchanged over networks.*

***Networks***

*A Network conducts material flows among entities. There are no a priori requirements regarding the structure of the network model. It might mimic the fine physical details of a distribution system, or a much coarser representation might be appropriate.*

***Services***

*Services take in materials and add value by transforming them into output materials. For example, a coal-fired power plant will take in coal, water, and labor and transform it into electricity. Each input or output material flow is usually a commercial transaction, modeled by a customer/supplier relationship.*

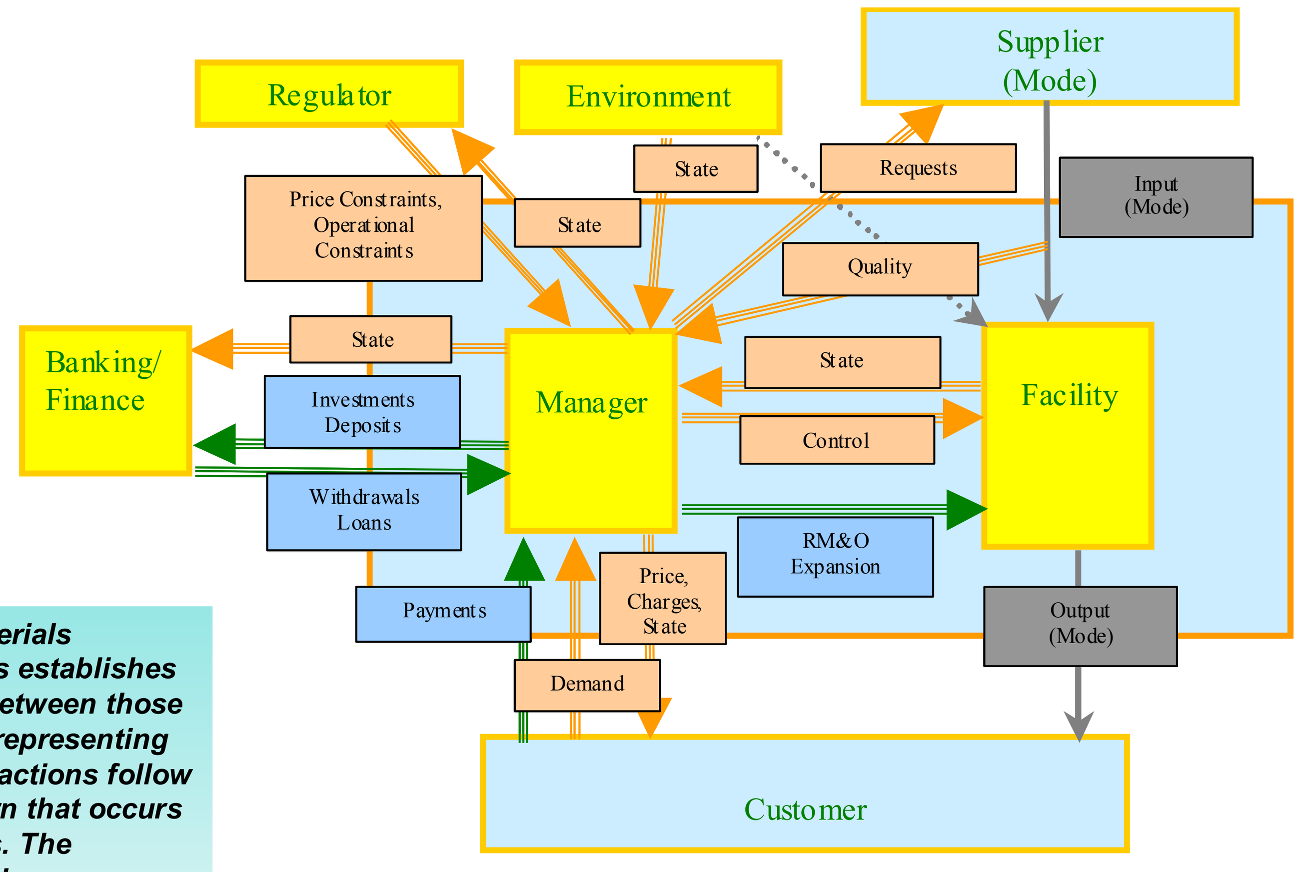
***Markets***

*Markets represent the way a set of material suppliers interacts with a set of customers for the material. Markets have one or more material suppliers, each offering their own price. They have one or more customers for the material, each paying a common price.*

***Entities***

*Entities are any other objects in the model that exchange materials. They are more general than services or markets because they are not required to provide any specific interface to other model components. Examples of entities include the environment, regulatory agencies, or financial institutions.*

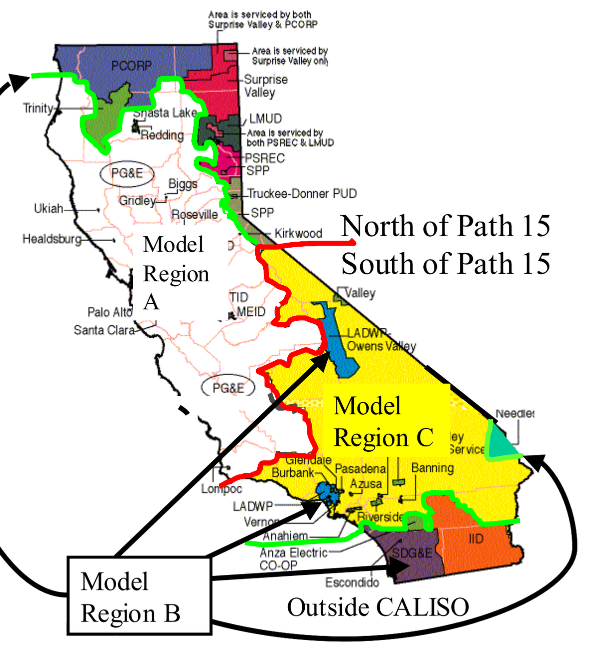
*The flow of materials between entities establishes a relationship between those entities. Flows representing economic transactions follow a distinct pattern that occurs in many models. The customer/supplier relationship exists between a service (the supplier) and any entity that uses one of the materials produced by the service. The relationship consists of four separate material flows:*




- *The supplier provides price information over a communications channel;*
- *The customer sends a demand for the material over a (separate) communications channel;*
- *The supplier sends the material to the customer, generally over a channel in a network that is suited to transmitting the material;*
- *The customer transmits payment to the supplier over the financial network.*

## Model Application to California Energy Systems

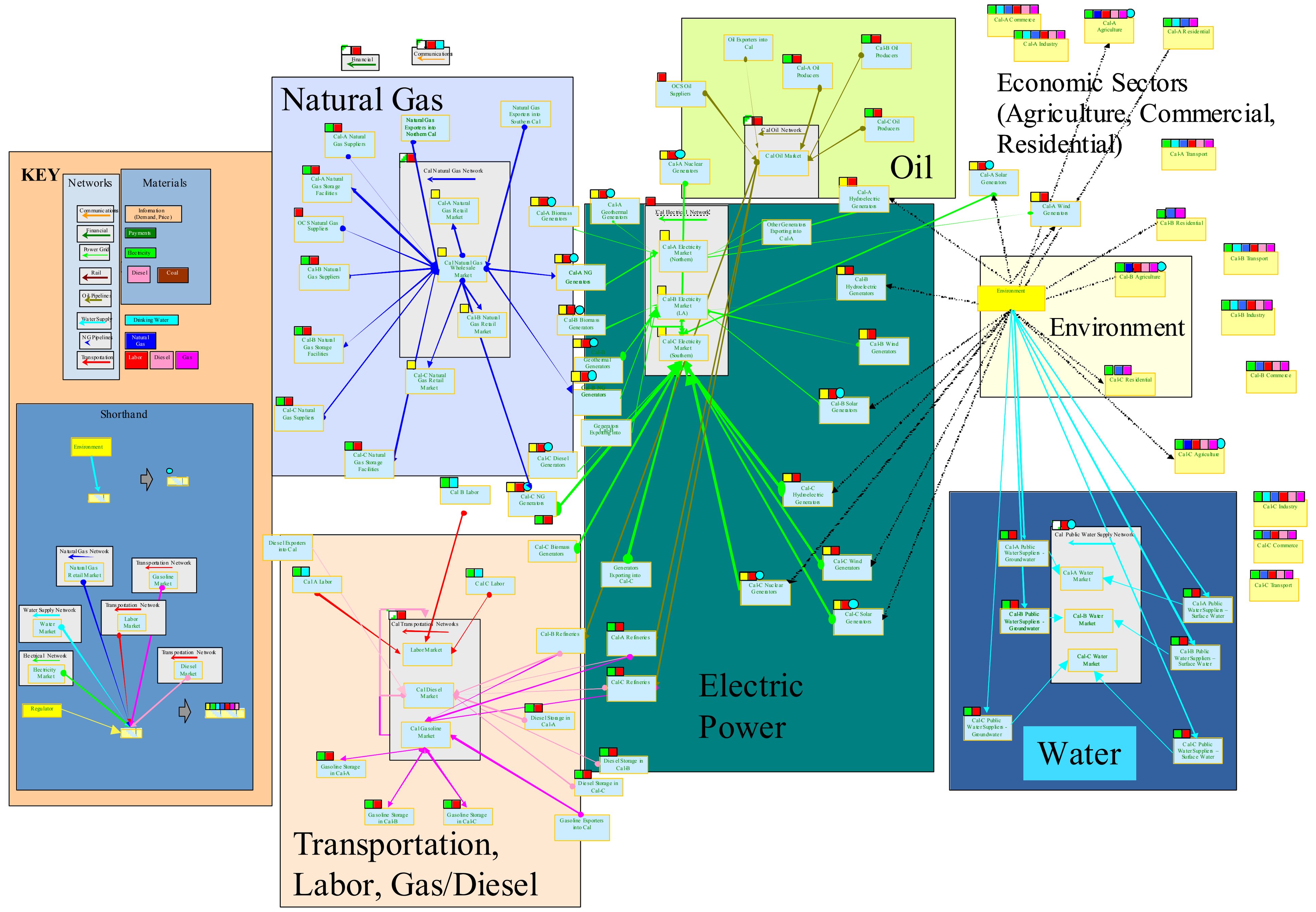
*We build infrastructure interdependency models from a set of components, each of which represents a particular infrastructure element, environmental context, or economic sector. Each component model represents the relevant internal dynamics, such as input material management, that govern the behavior of the infrastructure element. These component models exchange signals, representing the flow of materials, money, and information. A model of a particular system, such as the California electrical supply system and its associated customers, suppliers, and dependents, entails configuring the component dynamic simulation models and defining the way they are interconnected*




*Electric power supply in California depends on the interaction of a large number of processes, such as generator operation, power transmission and distribution, power marketing, and delivery of fuel to power generators.*

*In the winter of 2000-2001, trends in power supply and demand, along with plausible load projections for a warm summer, were considered likely to cause widespread shortages in electric power supply in California.*

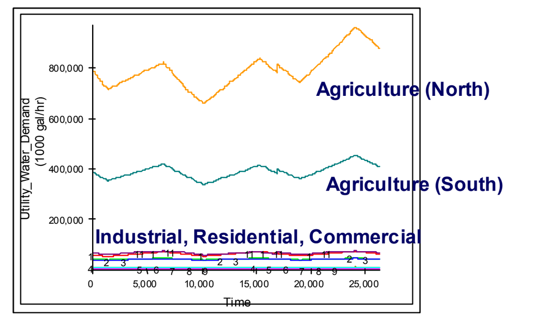
*We developed a set of interconnected dynamic simulation models to evaluate the potential costs of power outages, and the effectiveness of increased natural gas storage in improving power supply conditions.*



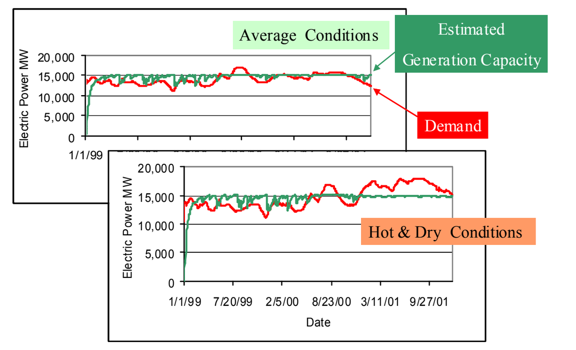

## Results

*Water – Agriculture – Electric Power Interdependencies*

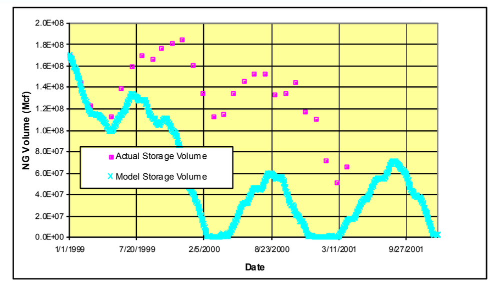
*Water Demand*




*Simulated Electric Power Supply in the Southern Cal ISO Region*




*Calculated and Historical Natural Gas in Storage*



*Hot and dry climate conditions can limit availability of hydro power, and increase reliance on other generation sources such as natural gas. This changes the seasonal demand for natural gas, and the conditions faced by gas production and storage facilities*

*The pricing behavior of storage services contains feedback loops through the commodity market. This feedback is responsible for some of the more interesting dynamical behavior observed in the model. During high demand periods, natural gas imports are constrained by pipeline capacity. The market price for gas therefore increases until storage release rates satisfy residual demand.*

### National Infrastructure Simulation & Analysis Center (NISAC)

*The National Infrastructure Simulation and Analysis Center (NISAC) is being established as the first comprehensive capability to assess the system of infrastructures and their interdependencies. NISAC's core partners are Sandia National Laboratories and Los Alamos National Laboratory.*

*Mission: Provide fundamentally new modeling and simulation capabilities for the analysis of critical infrastructures, their interdependencies, vulnerabilities, and complexities. These advanced capabilities will help improve the robustness of our Nation's critical infrastructures by aiding decision makers in the areas of policy analysis, investment and mitigation planning, education and training, and near real-time assistance to crisis response organizations.*

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